Optics Communications 591 (2025) 132029

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Hybrid three-dimensional power allocation for JIQ-NOMA based multi-user VLC systems ☆

Yuru Tang [a,c], Chen Chen [b,*], Xinke Tang [c,*], H.Y. Fu [a,c,**]

[a] Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen, 518055, Guangdong, China
[b] School of Microelectronics and Communication Engineering, Chongqing University, Chongqing, 400044, Chongqing, China
[c] Pengcheng Laboratory (PCL), Shenzhen, 518055, Guangdong, China

ARTICLE INFO

Keywords:
Visible light communication (VLC)
Three-dimensional power allocation (3DPA)
Joint in-phase and quadrature non-orthogonal multiple access (JIQ-NOMA)

ABSTRACT

Visible light communication (VLC) is an emerging technology for high-speed, short-range wireless communication. Power allocation among users in multi-user VLC systems is a critical issue that affects the system performance, particularly in the presence of varying channel conditions. In this paper, a novel three-dimensional power allocation (3DPA) scheme is proposed for joint in-phase and quadrature non-orthogonal multiple access (JIQ-NOMA) based multi-user VLC systems. The proposed 3DPA scheme aims to allocate power effectively among different user groups in VLC systems, thereby enhancing the overall system performance and improving fairness, particularly in light-based communication systems with varying channel conditions. Simulation results validate the effectiveness of the proposed 3DPA scheme, demonstrating a significant reduction of 1.8 dB in the transmitted signal-to-noise ratio (SNR) at a bit error rate (BER) of 3.8×10^{-3}, compared to the benchmark scheme. Furthermore, the transmission distance at this target BER can be increased by 14.1% relative to the benchmark scheme.

1. Introduction

Visible light communication (VLC), which utilizes commercially available light emitting diodes (LEDs), is increasingly recognized as a crucial enabling technology for the sixth-generation (6G) mobile networks and Internet of Things (IoT) systems [1,2]. VLC offers several advantages, including abundant and license-free spectrum resources, cost-effective front-end devices, and an absence of electromagnetic interference (EMI) radiation [3,4]. However, one limitation of VLC systems is the relatively low modulation bandwidth of commercial off-the-shelf LEDs, which is typically constrained to only a few MHz [5,6]. This limitation in modulation bandwidth restricts the achievable data transmission rates using standard LEDs, posing a challenge for their widespread adoption in communication applications.

To support multiple users efficiently in VLC systems, various multiple access techniques are employed [7]. These techniques can be broadly classified into two main categories: orthogonal multiple access (OMA) and non-orthogonal multiple access (NOMA) [8]. In OMA, users are assigned distinct orthogonal time or frequency resources, such as in frequency division multiple access (FDMA), orthogonal frequency division multiple access (OFDMA), and time division multiple access (TDMA) [9,10]. While OMA prevents user interference by allocating separate resources, it is inefficient in utilizing the available spectrum, leading to suboptimal performance, especially with a large number of users [11]. In contrast, NOMA offers a more efficient solution by enabling all users to share the same time and frequency resources. This is achieved through power domain superposition coding (SPC) and successive interference cancellation (SIC), which allow multiple users to transmit simultaneously while mitigating interference through advanced decoding techniques [12,13]. To further improve upon the capacity and performance of multi-user VLC systems, especially when handling a large number of users, a hybrid non-orthogonal multiple access/orthogonal frequency division multiple access (NOMA/OFDMA) scheme has been proposed [14]. This hybrid NOMA/OFDMA scheme combines the strengths of both NOMA and OFDMA to achieve efficient resource utilization while supporting a large number of users. In a hybrid NOMA/OFDMA-based multi-user VLC system, users are first paired

☆ This work was supported in part by Shenzhen Fundamental Research Program under Grant GXWD20201231165807007-20200827130534001, in part by the National Natural Science Foundation of China under Grant (62201303), in part by the Youth Science and Technology Innovation Talent of Guangdong Province under Grant 2019TQ05X227, and in part by National Natural Science Foundation of China under Grant 62271091.

* Corresponding authors.
** Corresponding author at: Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen, 518055, Guangdong, China.
E-mail addresses: tyr23@mails.tsinghua.edu.cn (Y. Tang), c.chen@cqu.edu.cn (C. Chen), tangxk@pcl.ac.cn (X. Tang), hyfu@sz.tsinghua.edu.cn (H.Y. Fu).

https://doi.org/10.1016/j.optcom.2025.132029
Received 8 March 2025; Received in revised form 21 May 2025; Accepted 23 May 2025
Available online 10 June 2025
0030-4018/

based on their channel conditions. Subsequently, OFDMA is employed to allocate different subcarriers to different user pairs, ensuring orthogonality between user pairs. Within each user pair, NOMA is applied so that the two users share the same time and frequency resources through power domain multiplexing. This hybrid approach effectively organizes users into multiple user pairs, enabling more efficient utilization of spectral resources.

Channel gain-based user pairing and grouping are widely employed as simple yet effective strategies in hybrid NOMA/ OFDMA-based multi-user VLC systems [15–17]. Based on their channel conditions, the sorted users are divided into multiple groups, where users with similar channel gains are grouped together. Subsequently, users with significant differences in channel gains are paired across different groups to exploit channel diversity and facilitate efficient power allocation strategies. By exploiting the disparity in channel gains between paired users, the system can effectively reduce intra-pair interference and enhance overall spectral efficiency. In addition, in practical IoT networks, connected devices exhibit diverse quality-of-service (QoS) requirements [1]. When QoS requirements are considered, users should be grouped to both optimize resource allocation and meet diverse service needs. Typically, IoT devices can be classified into low-speed devices, such as environmental sensors and health monitors, and high-speed devices, such as multimedia-capable mobile phones, reflecting their differing communication requirements. This categorization highlights the need for QoS-aware grouping strategies, although the present study adopts channel-based user pairing as a baseline approach.

Due to the nature of channel gain-based user pairing, user pairs in multi-user VLC systems inevitably experience power differences resulting from their diverse channel conditions [18]. These disparities in channel gains lead to varying levels of received signal strength. To address this issue and ensure fairness among the different user pairs, we previously proposed a fairness-aware hybrid NOMA/OFDMA scheme [14]. This proposed scheme employs subcarrier interleaving and utilizes a two-dimensional power allocation strategy, which simultaneously operates within the user pair (intra-pair) and between user pairs (inter-pair). While this approach effectively mitigates power disparities within pairs, the challenge of maintaining fairness across different user pairs remains. Additionally, to support a larger number of users within a single user group, we proposed a joint in-phase and quadrature non-orthogonal multiple access (JIQ-NOMA) scheme tailored for multi-user VLC systems [19]. Unlike traditional NOMA, which primarily relies on power domain superposition, JIQ-NOMA enhances system capacity by introducing an additional degree of freedom for power allocation through superposition in both the power and in-phase/quadrature (I/Q) domains. By utilizing both the in-phase (I) and quadrature (Q) components of the signal, JIQ-NOMA allows for independent implementation of NOMA in each domain, efficiently serving multiple users within the same group using pulse amplitude modulation (PAM). Despite these advancements, the issue of user unfairness persists among different user groups in JIQ-NOMA, primarily due to the significant variations in signal strength and path loss caused by users' different locations within the system. These differences in channel conditions can lead to an unequal distribution of resources, which undermines the fairness of the system and can affect overall performance.

To address this challenge, we propose a novel three-dimensional power allocation (3DPA) scheme for JIQ-NOMA based multi-user VLC systems. The 3DPA scheme is designed to ensure a more equitable distribution of resources across different user groups, thus improving fairness and enhancing overall system performance. The effectiveness and superiority of the proposed 3DPA scheme have been successfully validated through extensive simulation results, which demonstrate its significant improvements over the benchmark scheme in terms of both fairness and system performance.

2. System model

In this section, we first introduce the channel model of the VLC system, providing an overview of the key factors that influence signal transmission. We then discuss the principle of user grouping and pairing, explaining how users are grouped based on their channel conditions. Finally, we present our proposed hybrid 3DPA scheme for JIQ-NOMA based multi-user VLC systems, highlighting its advantages in improving system efficiency and fairness.

2.1. Channel model

In typical LED-based VLC systems, the direct current (DC) channel gain between the kth user and the LED transmitter can be accurately represented by

$$h_k = \frac{(m+1)\rho A}{2\pi d_k^2}\cos^m(\psi_k)T(\phi_k)g(\phi_k)\cos(\phi_k), \tag{1}$$

the Lambertian order of the LED transmitter, denoted by m, is calculated as $m = -\ln(2)/\ln(\cos(\Psi))$, where Ψ represents the semi-angle of the LED. This parameter characterizes the light intensity distribution emitted from the LED. The parameter ρ represents the responsivity of the photodiodes (PD), indicating the efficiency of the PD in converting incident light into an electrical signal, while A denotes the active area of the PD. The distance between the LED and the PD for the kth user is represented by d_k, and this distance plays a crucial role in signal attenuation. ψ_k and ϕ_k correspond to the emission and incident angles of the light, respectively, influencing the directionality and strength of the received signal. The term $T(\phi_k)$ refers to the transmission coefficient of the optical filter, which determines the amount of light passing through the filter at a specific angle. Finally, the optical lens gain, expressed as $g(\phi_k) = \frac{r^2}{\sin^2\Phi}$, depends on the refractive index r and the field-of-view (FOV) Φ of the optical lens, with both factors influencing the lens's ability to focus and direct light toward the PD.

Moreover, the additive noise in the VLC system usually includes both shot noise and thermal noise, which can be generally modeled as a real-valued zero-mean additive white Gaussian noise (AWGN) with power $Pn = N_0B$, where N_0 denotes the noise power spectral density (PSD) and B denotes the total available modulation bandwidth.

2.2. User grouping and pairing

In multi-user VLC systems with a large number of users, users are first grouped using OMA techniques based on their channel conditions. JIQ-NOMA is employed within each group. This dual-domain superposition allows each group to support up to four users, significantly increasing the overall system capacity. By denoting the number of groups as K, the total number of users that can be supported by the system is $4K$, providing a scalable solution for large user populations.

To group all $4K$ users, the channel gains obtained using (1) are first used to arrange them in descending order, as follows:

$$h_1 \geq \cdots \geq h_k \geq \cdots \geq h_{4K}, \tag{2}$$

subsequently, the $4K$ users are divided into four distinct user clusters: C_1, C_2, C_3, and C_4. In these user clusters, C_1 consists of users with relatively high channel gains, specifically from User 1 to User K, who has the best channel conditions. Following this descending order, C_2 includes users from $K+1$ to $2K$, C_3 covers users from $2K+1$ to $3K$, and C_4 contains users from $3K+1$ to $4K$, with each cluster representing a range of channel gains in decreasing order.

In JIQ-NOMA, since NOMA is applied separately in the I and Q domains, each group contains two pairs of users. Each pair consists of a user located relatively far from the LED (the "far user") and a user located relatively near the LED (the "near user"). Specifically, the first user pair (user pair Q) can be described as $U^i_{\text{pair, Q}}$, which is for NOMA implementation in the Q domain. Similarly, the second user pair (user

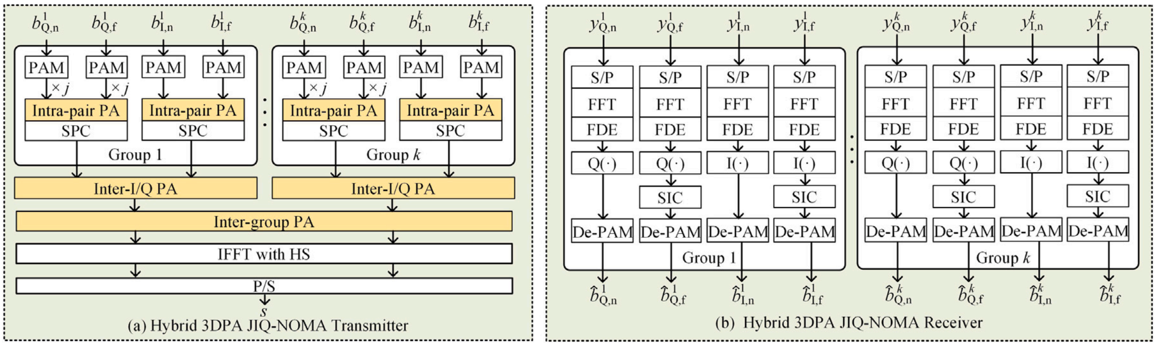

Fig. 1. Illustration of a k-group VLC system using JIQ-NOMA with hybrid 3DPA.

pair I) can be described as $U^{i}_{\text{pair, I}}$, which is for NOMA implementation in the I domain. To implement JIQ-NOMA, three different cases for user pairing are considered:

Case 1: For each group, two consecutive users are selected either from clusters C_1 and C_2, or from clusters C_3 and C_4. Specifically, for the first group, the first pair of users is selected from C_1 and C_2 as $U^{i,1}_{\text{pair, Q}} = [C_1(i), C_2(i)]$, where $C_1(i)$ and $C_2(i)$ represent the ith user from clusters C_1 and C_2, respectively. Similarly, the second pair of users is selected from C_1 and C_2 as $U^{i,1}_{\text{pair, I}} = [C_1(i+1), C_2(i+1)]$, where $C_1(i+1)$ and $C_2(i+1)$ are the $i+1$th user from clusters C_1 and C_2, respectively. The ith and $i+1$th groups for Case 1 are given by:

$$\begin{cases} \{C_1(i), C_1(i+1), C_2(i), C_2(i+1)\}, & \text{for Group } i \\ \{C_3(i), C_3(i+1), C_4(i), C_4(i+1)\}, & \text{for Group } i+1 \end{cases}, \tag{3}$$

this case selects consecutive users from each user cluster to form two groups, ensuring that each group consists of two user pairs with similar channel conditions. Therefore, the performance disparity within pairs can be reduced. However, this approach may lead to significant performance differences between groups, as users from distinct clusters may experience varying channel conditions.

Case 2: For each group, two consecutive users are selected either from clusters C_1 and C_3, or from clusters C_2 and C_4. Specifically, the first pair of users is selected from C_1 and C_3 as $U^{i,2}_{\text{pair, Q}} = [C_1(i), C_3(i)]$, where $C_1(i)$ and $C_3(i)$ are the ith user from clusters C_1 and C_3, respectively. Similarly, the second pair of users is selected from C_2 and C_4 as $U^{i,2}_{\text{pair, I}} = [C_2(i+1), C_4(i+1)]$, where $C_2(i+1)$ and $C_4(i+1)$ are the $(i+1)$th users from clusters C_2 and C_4, respectively. The ith and $i+1$th groups for Case 2 are expressed as:

$$\begin{cases} \{C_1(i), C_1(i+1), C_3(i), C_3(i+1)\}, & \text{for Group } i \\ \{C_2(i), C_2(i+1), C_4(i), C_4(i+1)\}, & \text{for Group } i+1 \end{cases}, \tag{4}$$

this case optimizes resource utilization and mitigates power disparities between users at varying distances from the LED transmitter by balancing user distribution across different clusters. This case would reduce the differences in the performance between groups.

Case 3: For each group, four users are selected by taking one user from each of the four clusters C_1, C_2, C_3, and C_4. The users are selected at equal intervals from each cluster, ensuring a uniform distribution of users across the clusters. Specifically, the set of users is represented as $U^{i,3}_{\text{group}} = [C_1(i), C_2(i), C_3(i), C_4(i)]$, where $C_j(i)$ denotes the ith user from cluster C_j $(j = 1, 2, 3, 4)$. In this case, two pairs of users are formed within each group: the first pair of users for NOMA in the Q domain is selected from $C_1(i)$ and $C_3(i)$ as $U^{i,3}_{\text{pair, Q}} = [C_1(i), C_3(i)]$, while the second pair of users for NOMA in the I domain is selected from $C_2(i)$ and $C_4(i)$ as $U^{i,3}_{\text{pair, I}} = [C_2(i), C_4(i)]$. The ith and $i+1$th groups for Case 3 are given by:

$$\begin{cases} \{C_1(i), C_2(i), C_3(i), C_4(i)\}, \\ \text{for Group } i \\ \{C_1(i+1), C_2(i+1), C_3(i+1), C_4(i+1)\}, \\ \text{for Group } i+1 \end{cases}, \tag{5}$$

this case ensures a uniform distribution of users across clusters, which would further reduce differences in the performance between groups.

For scenarios where the number of users is not equal to $4K$, conventional OMA or NOMA techniques can be applied to the remaining users beyond $4K$. To generalize to scenarios with more users, we partition N users into as many 8-user blocks as possible (each requiring 3DPA), then compute the remainder $r = N \bmod 8$ to determine the leftover users: if $r \geq 4$, a 4-user block undergoes 2DPA; if $2 \leq r < 4$, $\lfloor r/2 \rfloor$ 2-user block undergoes 1DPA; and if r is odd, the remaining single user is treated as a 1DPA "user pair". All blocks are then multiplexed via OFDMA. For example, when $N = 7$, we obtain one 4-user 2DPA block, one 2-user 1DPA block, and one single user treated as a 1DPA block; when $N = 10$, we obtain one 8-user 3DPA block and one 2-user 1DPA block; and when $N = 12$, we obtain one 8-user 3DPA block and one 4-user 2DPA block. This unified procedure ensures graceful degradation from 3DPA to 2DPA/1DPA and seamless handling of odd users.

2.3. Three-Dimensional Power Allocation (3DPA)

To eliminate the user unfairness within each user pair and user group caused by the varying channel conditions associated with different user locations, the 3DPA scheme is proposed. This proposed scheme effectively addresses the issue of performance disparity by incorporating multiple levels of power allocation strategies. Specifically, we employ the one-dimensional power allocation (1DPA) scheme, which focuses on intra-pair power allocation (PA) to ensure fairness within each user pair. The two-dimensional power allocation (2DPA) scheme, an extension of the 1DPA, considers both intra-pair power allocation PA and inter-I/Q PA to address performance differences across different user pairs. Finally, the 3DPA scheme builds upon the 2DPA by incorporating intra-pair PA, inter-I/Q PA, and inter-group PA, further mitigating unfairness across user groups and enhancing overall system performance and user experience.

In this study, we assume a fixed total transmitted power, considering the LED peak-power limitations that restrict signal strength. While increasing power for one group reduces the available power for others, the proposed 3DPA scheme enhances system performance, especially when LED linearization techniques are applied to extend the effective linear range. As illustrated in Fig. 1(a), for one group in the hybrid 3DPA JIQ-NOMA transmitter, $b^{k}_{Q,\text{n}}$ and $b^{k}_{Q,\text{f}}$ denote the input bit streams to be transmitted to the near and far users in the user pair Q, respectively. Similarly, $b^{k}_{I,\text{n}}$ and $b^{k}_{I,\text{f}}$ are the input bit streams to be transmitted to the near and far users in the user pair I, respectively. These binary data streams are mapped into PAM constellation symbols for user pair I and user pair Q via the intra-pair PA. Subsequently, these symbols are assigned different power levels, and the SPC is applied for transmission. To balance the transmit power difference between the far and near users within each user pair, the intra-pair PA ratios for one user group,

α_{I} and α_{Q}, are given by

$$\begin{cases} \alpha_{\mathrm{I}} = \dfrac{P_{\mathrm{I,n}}}{P_{\mathrm{I,f}}} \\ \alpha_{\mathrm{Q}} = \dfrac{P_{\mathrm{Q,n}}}{P_{\mathrm{Q,f}}} \end{cases}, \tag{6}$$

where $P_{\mathrm{I,n}}$, $P_{\mathrm{I,f}}$, $P_{\mathrm{Q,n}}$, and $P_{\mathrm{Q,f}}$ are the allocated electrical transmit power levels for the signal components intended for different users. Within each user pair, since the far user with a smaller channel gain needs to be allocated more power than the near user with a higher channel gain, we have $0 < \alpha_{\mathrm{I}} < 1$ and $0 < \alpha_{\mathrm{Q}} < 1$.

To further balance the power difference across two different user pairs, a power allocation ratio between signals transmitted via the I channel and the Q channel is also considered, which is referred to as the inter-I/Q PA ratio, β, and is given by

$$\beta = \frac{P_{\mathrm{Q}}}{P_{\mathrm{I}}}, \tag{7}$$

where P_{Q} and P_{I} are the allocated electrical transmit power levels for the user pair Q and user pair I, respectively. Without loss of generality, we assume that user pair I has a smaller overall channel gain than user pair Q and thus it is reasonable to allocate more power to user pair I. As a result, we have $0 < \beta < 1$.

However, the user group unfairness still exists after inter-I/Q PA due to the overall channel gain difference between different user groups. Hence, the inter-group PA scheme is proposed and the inter-group PA ratio, θ, is given by

$$\theta = \frac{P_{\mathrm{G1}}}{P_{\mathrm{G2}}}, \tag{8}$$

where P_{G1} and P_{G2} are the allocated electrical transmit power levels for different user groups. We assume the user group allocated with P_{G1} has less power; hence, we have $0 < \theta < 1$.

Similar to conventional optical OFDM modulation, the constellation symbols assigned to different OFDM subcarriers are required to exhibit Hermitian symmetry (HS) before applying the inverse fast Fourier transform (IFFT) and the parallel-to-serial (P/S) conversion. This ensures that the transmitted signal is real-valued, which is essential for efficient optical transmission. Finally, the resulting time-domain JIQ-NOMA signal, s, is used to directly drive the LED for optical signal transmission, where the LED emits the modulated optical signal to the receivers.

In the hybrid 3DPA JIQ-NOMA receiver, as illustrated in Fig. 1(b), the received signals from different users within a group, $y^k_{I,\mathrm{n}}$, $y^k_{I,\mathrm{f}}$, $y^k_{Q,\mathrm{n}}$, and $y^k_{Q,\mathrm{f}}$, first undergo serial-to-parallel (S/P) conversion, after which they are transformed into the frequency domain through fast Fourier transform (FFT). This transformation enables frequency-domain equalization (FDE), which is crucial for compensating for channel distortions and ensuring accurate signal recovery. After the equalization process, the signals for the Q domain and I domain user pairs are separated. For each user pair, the bit stream for the far user is directly recovered through PAM demapping, while the bit stream for the near user is obtained through SIC followed by PAM demapping, enabling efficient separation of the signals and improving the overall decoding performance. A pseudo 16-QAM signal generated by superimposing four 2-PAM modulated signals can be used to explain the SIC decoding process [19]. The composite constellation is initially separated into its I and Q components, creating two distinct user pairs. In each pair, the user with the stronger signal decodes their transmission directly, treating the interference from their partner's signal as noise. Meanwhile, the other user applies SIC by first decoding the interfering signal, and then subtracting it from the composite signal to isolate and decode their own data.

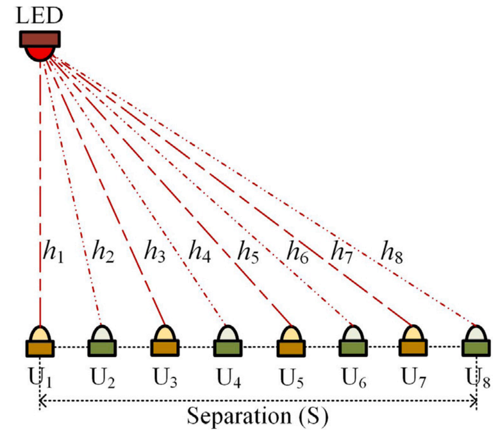

Fig. 2. Simulation setup of two user groups VLC system.

Table 1
Simulation parameters.

Parameter	Value
Distance between LED and U1	2.15 m
Semi-angle at half power of LED	70°
Gain of optical filter	0.9
Refractive index of optical lens	1.5
Half-angle FOV of optical lens	70°
Responsivity of PD	0.53 A/W
Active area of PD	1 cm^2
Signal bandwidth	20 MHz
Noise power spectral density	10^{-22} A^2/Hz
Modulation scheme	2-PAM

3. Simulation results

In this section, we evaluate the proposed hybrid 3DPA scheme and compare it with the conventional 2DPA scheme in JIQ NOMA-based eight-user VLC systems. It is important to note that the primary focus of this study is to examine the impact of user grouping. Therefore, a comparison is made between the 2DPA and 3DPA schemes, both of which employ the same user grouping strategy. Since α and β are determined by the channel gains of the users, and the grouping strategy is identical in both 2DPA and 3DPA, the values of α and β are the same in both schemes.

In our simulation, we consider an indoor room with a dimension of 5 m × 5 m × 3 m, where the LED is located at the center of the ceiling and the height of the receiving plane is 0.85 m. For simplicity and without loss of generality, we consider eight users divided into two groups, and we assume that eight users are evenly spaced, with the nearest user located directly beneath the LED and the farthest user located at a horizontal separation S from the LED, where $S = 3$ m. In Case 1, Group 1 is defined as $U^{1,1}_{\mathrm{group}} = \{U_1, U_2, U_3, U_4\}$ and Group 2 as $U^{2,1}_{\mathrm{group}} = \{U_5, U_6, U_7, U_8\}$. In Case 2, Group 1 is defined as $U^{1,2}_{\mathrm{group}} = \{U_1, U_2, U_5, U_6\}$ and Group 2 as $U^{2,2}_{\mathrm{group}} = \{U_3, U_4, U_7, U_8\}$. For Case 3, Group 1 is defined as $U^{1,3}_{\mathrm{group}} = \{U_1, U_3, U_5, U_7\}$ and Group 2 as $U^{2,3}_{\mathrm{group}} = \{U_2, U_4, U_6, U_8\}$. Fig. 2 illustrates the simulation setup for the multi-user VLC system in Case 3. The simulation is performed using MATLAB R2023b. The key simulation parameters for the bandlimited eight-user VLC system are summarized in Table 1. The system includes one LED with a 70° semi-angle at half power, and each user is equipped with a photodiode (PD) featuring a responsivity of 0.53 A/W and an active area of 1 cm^2. Additionally, the refractive index of the optical lens is set to 1.5, with a half-angle FOV of 70°. The signal bandwidth utilized in the simulation is 50 MHz, the noise power spectral density (PSD) is specified as 10^{-22} A^2/Hz, and the modulation scheme is 2PAM. Specifically, transmitted SNR is defined as the ratio of the transmitted

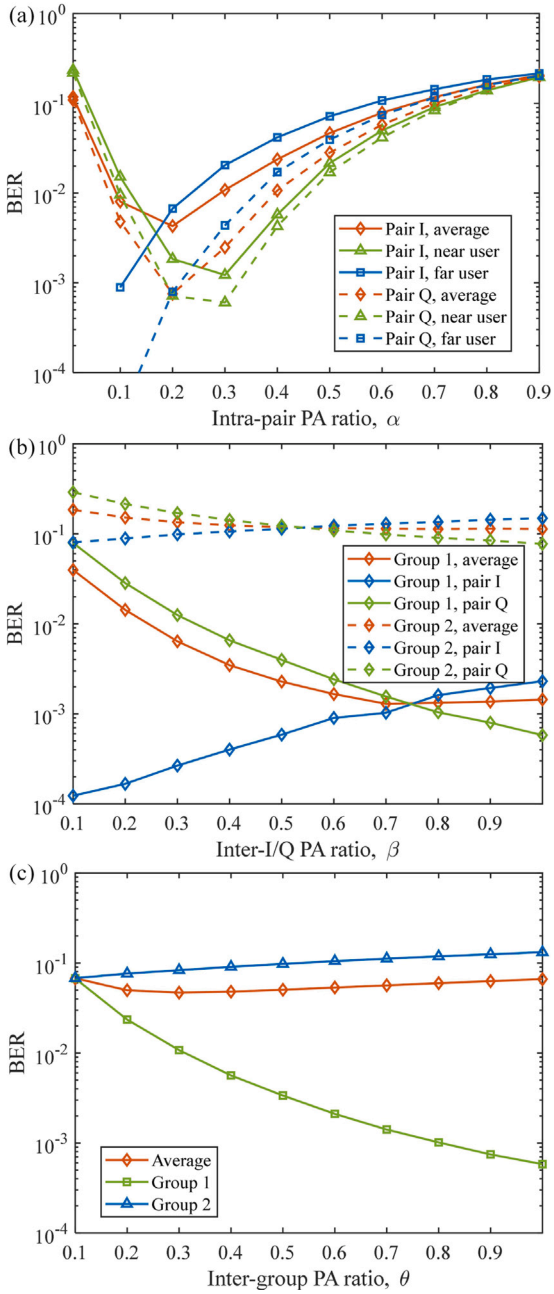

Fig. 3. (a) BER vs. intra-pair PA ratio α, (b) BER vs. inter-I/Q PA ratio β and (c) BER vs. inter-group PA ratio θ.

electrical signal power to the additive noise power. Based on our simulation parameters, the channel gain is on the order of 10^{-6}, which implies a severe attenuation of approximately 120 dB at the receiver. Hence, in our simulations, the transmitted SNR is set in the range of 125 to 140 dB [20]. Specifically, for a transmitted SNR of 128 dB and $S = 3$ m, the calculated channel gains for the eight users are $h_1 = 3.0510 \times 10^{-6}$, $h_2 = 2.8418 \times 10^{-6}$, $h_3 = 2.3316 \times 10^{-6}$, $h_4 = 1.7474 \times 10^{-6}$, $h_5 = 1.2440 \times 10^{-6}$, $h_6 = 8.6754 \times 10^{-7}$, $h_7 = 6.0441 \times 10^{-7}$, and $h_8 = 4.2536 \times 10^{-7}$.

Fig. 3(a), (b), and (c) illustrate the bit error rate (BER) as a function of the intra-pair PA ratio α, inter-I/Q PA ratio β, and inter-group PA ratio θ, respectively. Simulations were performed based on Case 1 with $S = 3$ m and a transmitted SNR of 128 dB. As shown in Fig. 3(a), within each user pair, an increase in α results in a progressive deterioration of the far user's performance, as indicated by a continuously rising BER. In contrast, the near user initially benefits from a reduction in BER with increasing α; however, as α continues to increase, error propagation effects become significant, ultimately leading to a rise in the near user's BER. The optimal value of α is found to be 0.2 after intra-pair PA for a single user group. Fig. 3(b) shows that as the value of β increases, more power is allocated to the signals intended for the users in the user pair Q, while less power is allocated to the users in the user pair I. This results in a reduction in the BER for the user pair Q and an increase in the BER for the user pair I. Specifically, after inter-IQ PA for a single user group, the optimal β values are 0.7 for Group 1 and 0.8 for Group 2. To obtain the optimal value of θ, we first fix α and β at their optimal values, as obtained in previous steps. Fig. 3(c) shows the BER versus θ under the optimal values of α and β. As θ increases, more power is allocated to Group 1 and less to Group 2, which results in the BER reduction of Group 1 and the BER augmentation of Group 2. And the optimal θ is 0.3 after inter-group PA for a two user groups.

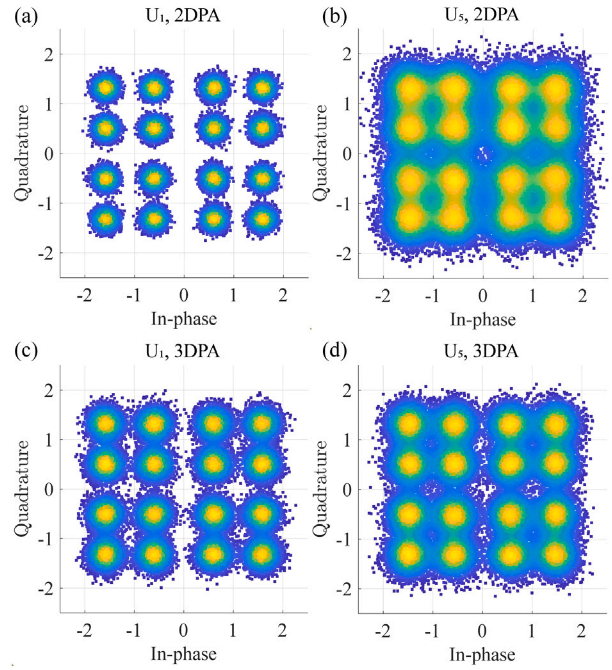

Fig. 4. Constellation diagrams for (a) U_1 under 2DPA, (b) U_5 under 2DPA, (c) U_1 under 3DPA, and (d) U_5 under 3DPA.

To further illustrate how 3DPA modifies constellation shapes, Fig. 4(a)–(d) present the received constellation diagrams of U_1 from Group 1 and U_5 from Group 2 under both the 2DPA and 3DPA schemes, at a transmitted SNR of 130 dB and $S = 3$ m in Case 1. In these figures, $\alpha = 0.2$ and $\beta = 0.7$ are set for 2DPA, while $\alpha = 0.2$, $\beta = 0.8$, and $\theta = 0.3$ are set for 3DPA. Each user employs 2-PAM modulation; within each user pair, SPC generates a 4-PAM constellation according to the intra-pair PA ratio. By applying the inter-I/Q PA ratio, a subsequent SPC stage produces an overall 16-QAM constellation. Finally, inter-group PA adjusts the transmitted power of each user group. Under 2DPA, as shown in Fig. 4(a) and (b), U_1 and U_5 are allocated equal transmitted power and occupy separate carriers, resulting in independent constellations. Additionally, owing to their different channel conditions, the noise components in the received constellations vary significantly. In contrast, under 3DPA, as shown in Fig. 4(c) and (d), the inter-group PA ratio θ leads to unequal power allocation. Specifically, less power is allocated to Group 1 with larger overall channel gain and more power is allocated to Group 2 with smaller overall channel gain. Consequently, at the receiver side, the constellation points of U_1 in are more widely scattered than under 2DPA, whereas those of U_5 are more tightly clustered compared to 2DPA.

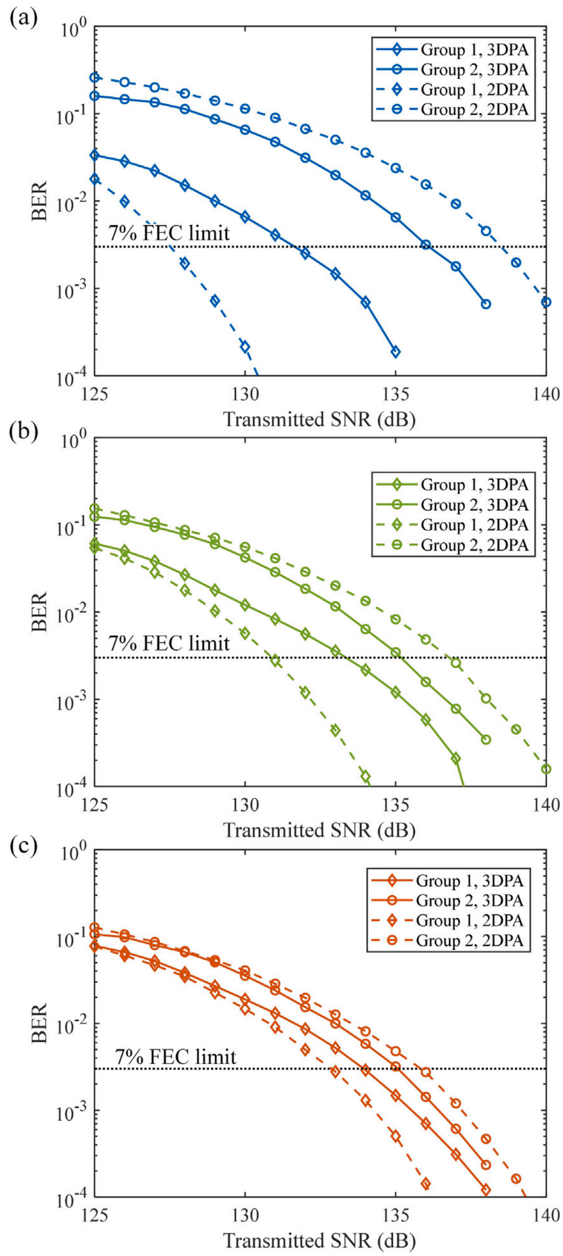

Fig. 5. BER vs. transmitted SNR for (a) case 1, (b) case 2 and (c) case 3.

Fig. 5 illustrates the BER as a function of transmitted SNR for three cases in which S is set to 3 m. In all cases, the BER curves of the two user groups under the 3DPA scheme are closer together than under the 2DPA scheme. Since each case represents different user grouping and pairing scenarios, in Case 1, as shown in Fig. 5(a), the physical distance between the two user groups is the largest, leading to the most significant difference in the BER curves between the groups when compared to Case 2 and Case 3. This indicates that the 3DPA scheme mitigates performance disparities between user groups, thereby improving fairness and demonstrating superior effectiveness.

Fig. 6 illustrates the average BER of Group 1 and Group 2 as a function of transmitted SNR for three different cases with $S = 3$ m. In every case, the 3DPA scheme outperforms the conventional 2DPA scheme by lowering the transmitted SNR required to achieve the 7% forward error correction (FEC) limit of BER = 3.8×10^{-3}. Specifically, to reach this FEC limit, the required SNR is reduced by 1.8 dB in Case 1, 1.2 dB in Case 2, and 0.4 dB in Case 3. The most pronounced

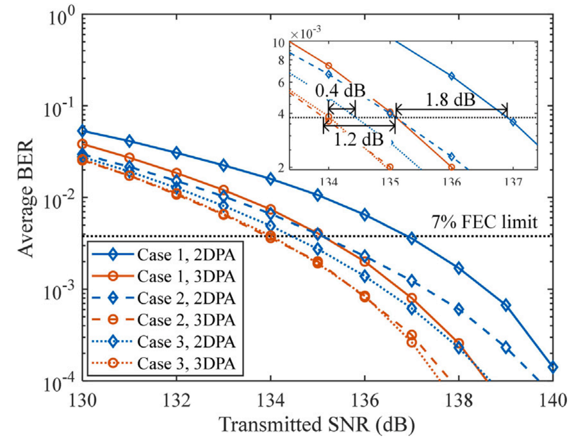

Fig. 6. Average BER vs. transmitted SNR under three cases.

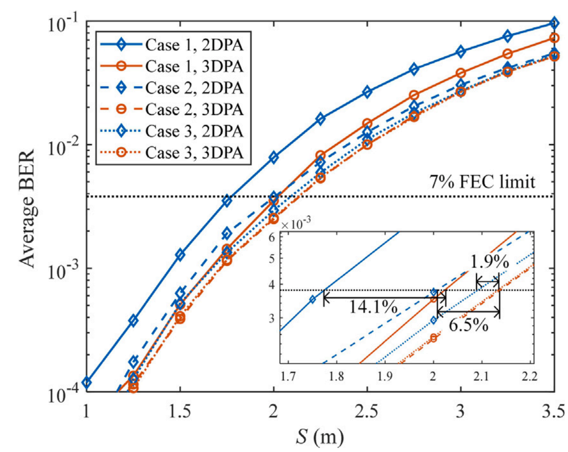

Fig. 7. Average BER vs. S under three cases.

improvement in Case 1 stems from its largest channel-gain disparity between the two user groups, which allows 3DPA to rebalance power most effectively.

Fig. 7 depicts the average BER of Group 1 and Group 2 as a function of S for three different cases at a transmitted SNR of 130 dB. In each case, the overall average BER increases as S grows. Under the conventional 2DPA scheme, the BER reaches the FEC limit at a smaller S, whereas the proposed 3DPA scheme enables larger S while maintaining acceptable BER levels. Specifically, compared to the 2DPA scheme, 3DPA achieves a 14.1% extension in allowable S for Case 1, a 6.5% extension for Case 2, and a 1.9% extension for Case 3. These results confirm that 3DPA not only enhances BER performance but also expands the system's operational range, thereby improving robustness under spatially uneven channel conditions.

4. Conclusion

In this paper, we have proposed and evaluated a hybrid 3DPA scheme for JIQ-NOMA-based multi-user VLC systems. The proposed scheme addresses the fairness issue among different user groups by mitigating the power differences caused by varying channel conditions. Compared to the traditional 2DPA scheme, the 3DPA scheme significantly reduces these power imbalances. Simulation results confirm that the hybrid 3DPA scheme effectively improves the BER performance of an eight-user VLC system, demonstrating its potential to enhance system reliability and user fairness. Therefore, the proposed hybrid

3DPA scheme is promising for JIQ-NOMA based multi-user VLC systems. Future research will extend the current study by investigating the integration of JIQ-NOMA into multiple-input multiple-output VLC systems as well as multi-cell VLC networks.

CRediT authorship contribution statement

Yuru Tang: Writing – original draft, Validation, Investigation, Formal analysis, Conceptualization. **Chen Chen:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Xinke Tang:** Writing – review & editing, Project administration, Formal analysis. **H.Y. Fu:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] Chen Chen, Shu Fu, Xin Jian, Min Liu, Xiong Deng, Zhiguo Ding, NOMA for energy-efficient LiFi-enabled bidirectional IoT communication, IEEE Trans. Commun. 69 (3) (2021) 1693–1706.

[2] Luiz Eduardo Mendes Matheus, Alex Borges Vieira, Luiz F.M. Vieira, Marcos A.M. Vieira, Omprakash Gnawali, Visible light communication: Concepts, applications and challenges, IEEE Commun. Surv. Tutor. 21 (4) (2019) 3204–3237.

[3] Xiong Deng, Kumar Arulandu, Yan Wu, Shokoufeh Mardanikorani, Guofu Zhou, Jean-Paul M.G. Linnartz, Modeling and analysis of transmitter performance in visible light communications, IEEE Trans. Veh. Technol. 68 (3) (2019) 2316–2331.

[4] Li Chen, Weidong Wang, Chi Zhang, Coalition formation for interference management in visible light communication networks, IEEE Trans. Veh. Technol. 66 (8) (2017) 7278–7285.

[5] Kai Ying, Zhenhua Yu, Robert J Baxley, Hua Qian, Gee-Kung Chang, G Tong Zhou, Nonlinear distortion mitigation in visible light communications, IEEE Wirel. Commun. 22 (2) (2015) 36–45.

[6] Chen Chen, Xin Zhong, Shu Fu, Xin Jian, Min Liu, Helin Yang, Arokiaswami Alphones, H.Y. Fu, OFDM-based generalized optical MIMO, J. Lightwave Technol. 39 (19) (2021) 6063–6075.

[7] Bruno Clerckx, Yijie Mao, Zhaohui Yang, Mingzhe Chen, Ahmed Alkhateeb, Liang Liu, Min Qiu, Jinhong Yuan, Vincent W.S. Wong, Juan Montojo, Multiple access techniques for intelligent and multifunctional 6G: Tutorial, survey, and outlook, Proc. IEEE 112 (7) (2024) 832–879.

[8] Mohanad Obeed, Anas M Salhab, Mohamed-Slim Alouini, Salam A Zummo, On optimizing VLC networks for downlink multi-user transmission: A survey, IEEE Commun. Surv. Tutor. 21 (3) (2019) 2947–2976.

[9] Jiun-Yu Sung, Chien-Hung Yeh, Chi-Wai Chow, Wan-Feng Lin, Yang Liu, Orthogonal frequency-division multiplexing access (OFDMA) based wireless visible light communication (VLC) system, Opt. Commun. 355 (2015) 261–268.

[10] Amr M. Abdelhady, Osama Amin, Anas Chaaban, Basem Shihada, Mohamed-Slim Alouini, Downlink resource allocation for dynamic TDMA-based VLC systems, IEEE Trans. Wirel. Commun. 18 (1) (2019) 108–120.

[11] Zhihong Zeng, Yuhan Du, Yangping Qian, Min Liu, Chen Chen, Index modulation multiple access-aided multi-user VLC for internet of medical things, Opt. Express 32 (25) (2024) 44478–44487.

[12] Hanaa Marshoud, Vasileios M Kapinas, George K Karagiannidis, Sami Muhaidat, Non-orthogonal multiple access for visible light communications, IEEE Photonics Technol. Lett. 28 (1) (2015) 51–54.

[13] Yuanwei Liu, Chongjun Ouyang, Zhiguo Ding, Robert Schober, The road to next-generation multiple access: A 50-year tutorial review, Proc. IEEE 112 (9) (2024) 1100–1148.

[14] Chen Chen, Yuru Tang, Yueping Cai, Min Liu, Fairness-aware hybrid NOMA/OFDMA for bandlimited multi-user VLC systems, Opt. Express 29 (25) (2021) 42265–42275.

[15] Esam M. Almohimmah, Mohammed T. Alresheedi, Ahmad F. Abas, Jaafar Elmirghani, A simple user grouping and pairing scheme for non-orthogonal multiple access in VLC system, in: 20th International Conference on Transparent Optical Networks, ICTON, 2018, pp. 1–4.

[16] Liang Yin, Wasiu O. Popoola, Xiping Wu, Harald Haas, Performance evaluation of non-orthogonal multiple access in visible light communication, IEEE Trans. Commun. 64 (12) (2016) 5162–5175.

[17] Muhammad Bilal Janjua, Daniel Benevides da Costa, Hüseyin Arslan, User pairing and power allocation strategies for 3D VLC-NOMA systems, IEEE Wirel. Commun. Lett. 9 (6) (2020) 866–870.

[18] Qian Li, Tao Shang, Tang Tang, Zehui Xiong, Adaptive user association scheme for indoor multi-user NOMA-VLC systems, IEEE Wirel. Commun. Lett. 12 (5) (2023) 873–877.

[19] Yuru Tang, Chen Chen, Cuiwei He, Bohua Deng, Min Liu, Xinke Tang, H.Y. Fu, Harald Haas, Joint in-phase and quadrature non-orthogonal multiple access for multi-user VLC, J. Lightwave Technol. 42 (20) (2024) 7219–7228.

[20] Qinghua Zhou, Xueyang Hu, Junting Lin, Zhongqing Wu, Train-to-train communication resource allocation scheme for train control system, in: 2018 10th International Conference on Communication Software and Networks, ICCSN, 2018, pp. 210–214.